

Solar Radiation Measurements:

A Workshop For

The National Association of State Universities
and Land Grant Colleges

By

Tom Stoffel & Steve Wilcox

Hydrogen & Electric Technologies & Systems Center

August 4, 2004



Outline

- Introductions
- *Shining On, A Primer on Solar Radiation Data*
 - What are solar radiation measurements?
 - Why do we need solar radiation data?
 - What influences the amount of solar radiation?
 - How do we use solar radiation data?
 - How accurate do the data need to be?
- How are we meeting our solar radiation data needs?
- Where can you obtain solar radiation data?
- Pop Quiz
 - No acronyms!

Introductions

Tom Stoffel & Steve Wilcox

Resource Integration Group

Measurement & Instrumentation Team

Geographic Information System Team

40+ years experience:

- Solar measurement station/network design
 - SRRL, HBCU, Saudi, DOE/ARM, NOAA, WMO/BSRN, GAW
- Radiometer calibration and characterization
 - BORCAL/RCC
 - IPCs, NPCs
- Solar data quality assessment
 - SERI-QC
 - DQMS

What are Solar Radiation Measurements?

Energy from the Sun at the Earth's Surface

- Different parts of the sky
- Change with time (minutes, hours)
- Change with time (seasons, years, decades)
- Change with location



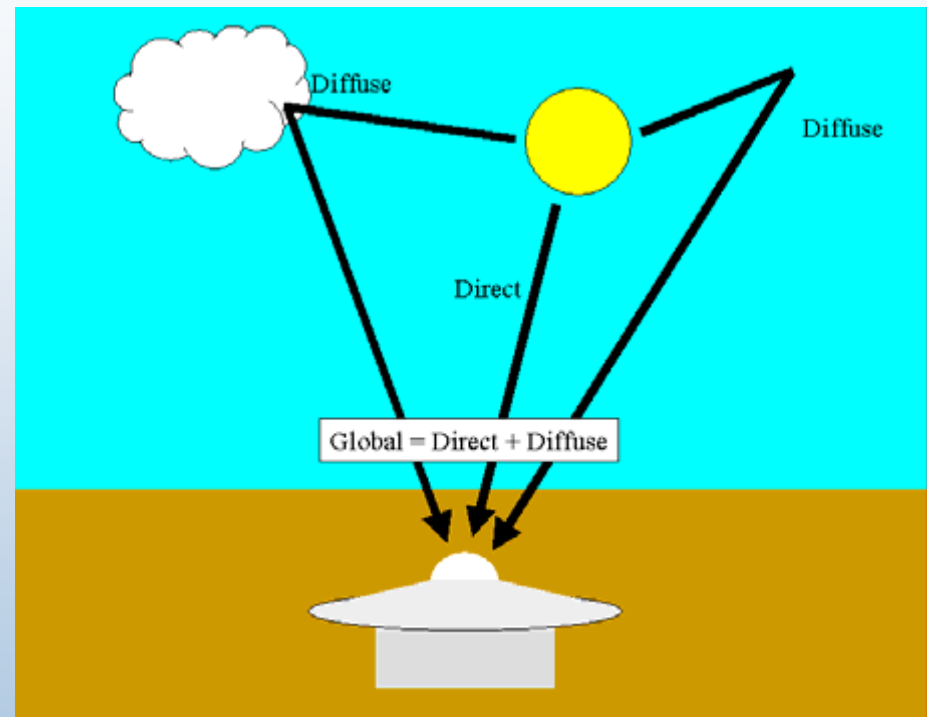
What are Solar Radiation Measurements?

Light from the sky dome

- Direct from the sun
- Everywhere but the sun
- Entire sky

We call it

- Direct (beam)
- Diffuse (sky)
- Global (total)



Global is the sum of direct and diffuse

What are Solar Radiation Measurements?

Direct Normal

Measured by a *Pyrheliometer* on a sun-following tracker



Global Horizontal

Measured by a *Pyranometer* with a horizontal sensor



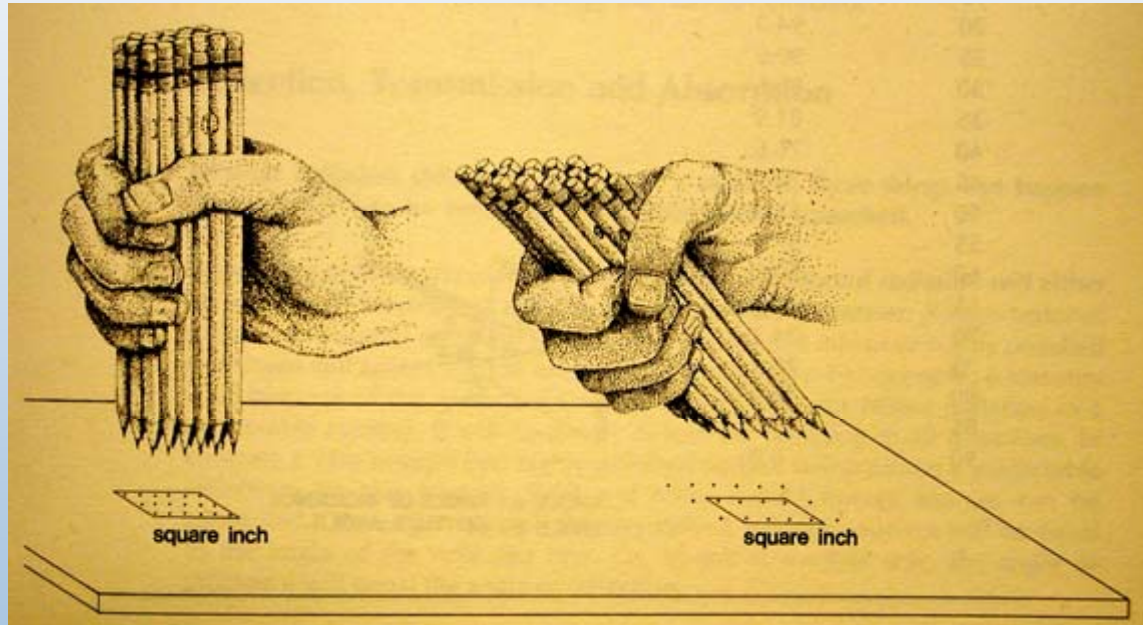
Diffuse

Measured by a shaded *Pyranometer* under a tracking ball



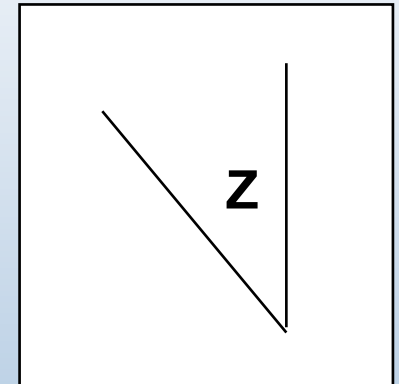
Solar Irradiance Components

$$\text{Global} = \text{Direct Normal} * \cos(Z) + \text{Diffuse}$$



18 dots

8 dots



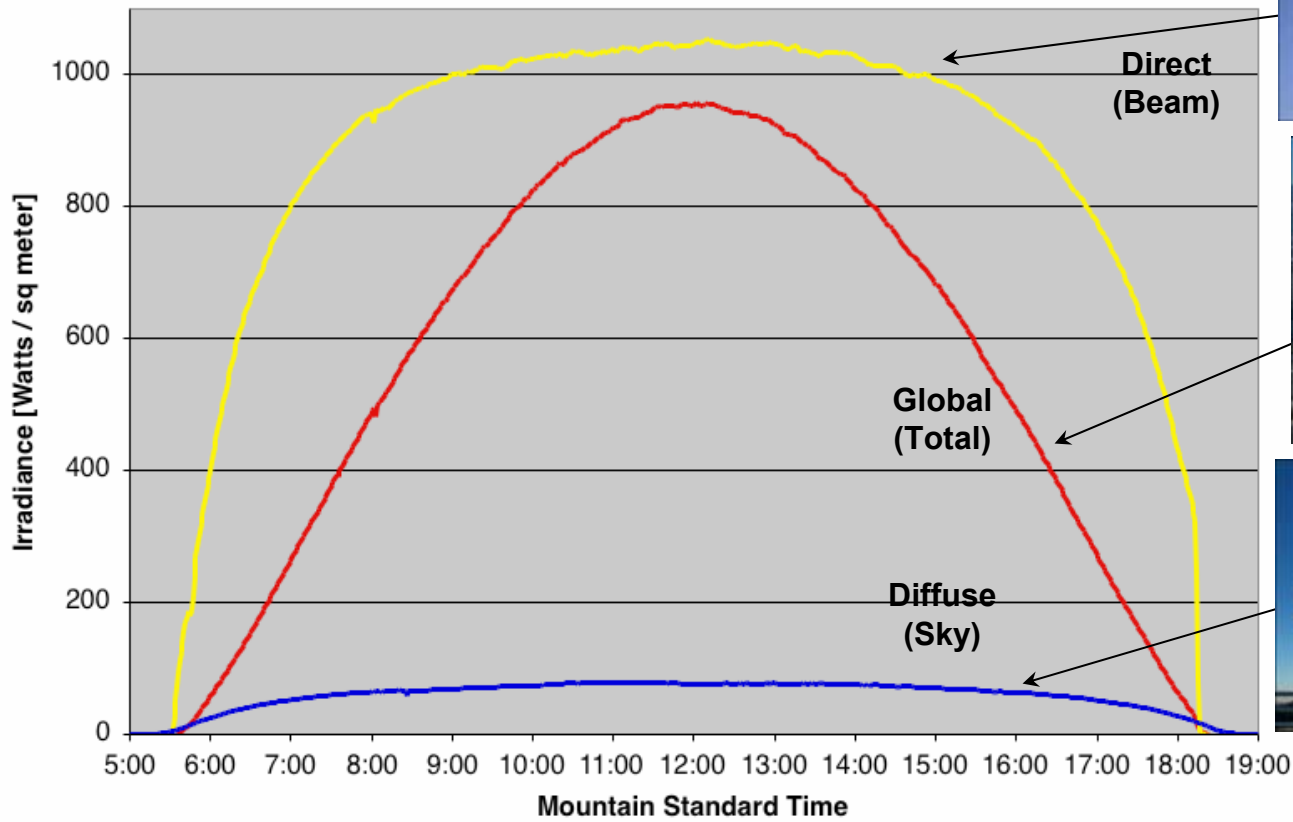
$$\cos(Z) = 8/18$$

$$Z = \cos^{-1}(0.4444)$$

$$Z = 63.6^\circ$$

Clear Sky

Solar Irradiance Measurements
Golden, Colorado 9 April 2003



<http://www.nrel.gov/srrl>

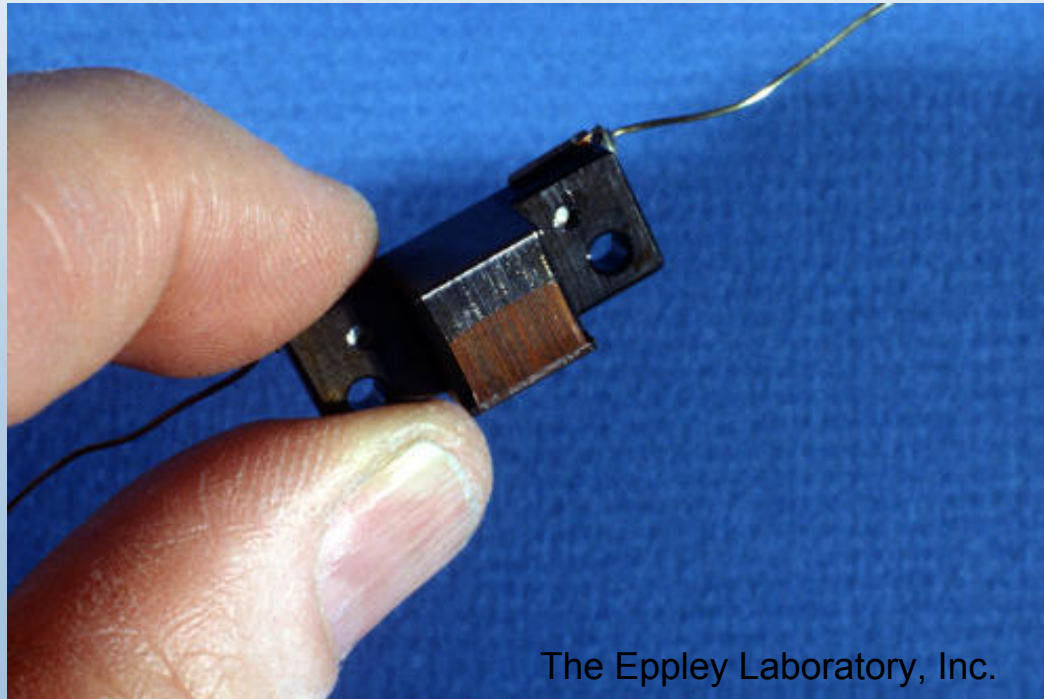
Thermopile Detectors

How do the radiometers work?

Thermo-electric detectors:

Two metals + Heat = Electrical Current

Copper-Constantan wire wound *Thermopiles*



The Eppley Laboratory, Inc.

Thermopile Detectors

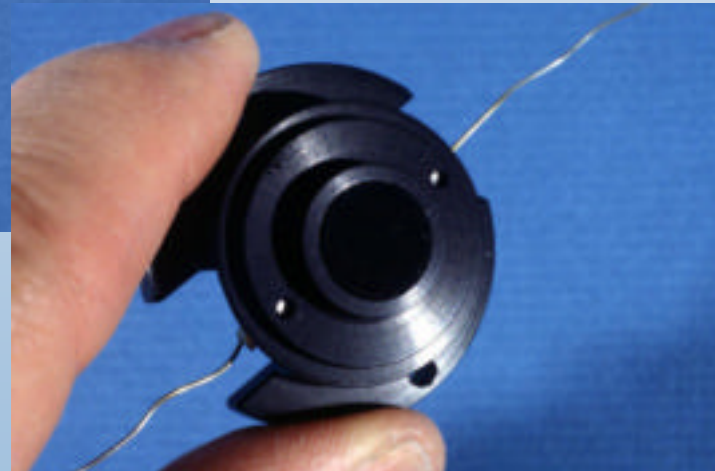


Pyrheliometer

1st Class \$, Flat Spectral Response, “Slow”



Pyranometer



The Eppley Laboratory, Inc.

Photoelectric Detectors

Fast, Low-Cost, with Reduced Spectral Response:



www.kippzonen.com



www.licor.com

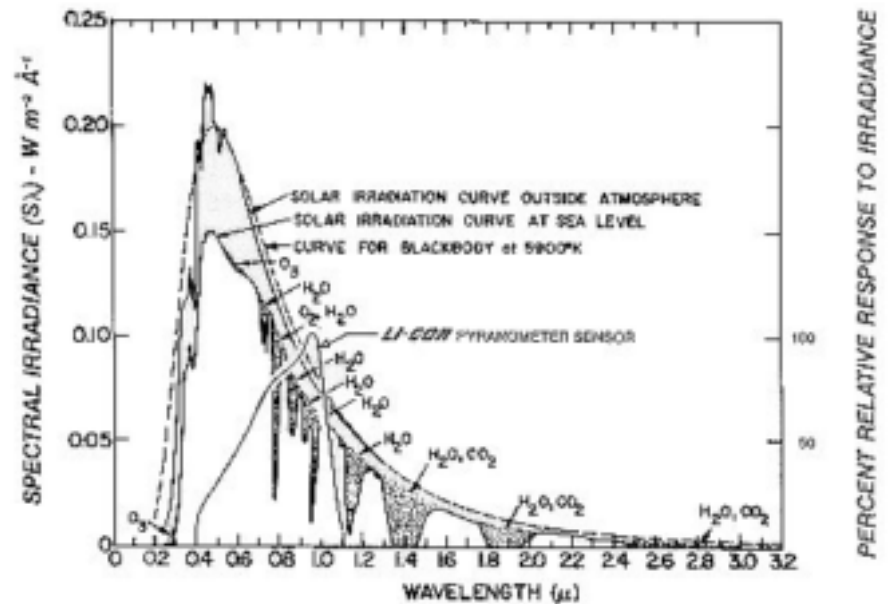
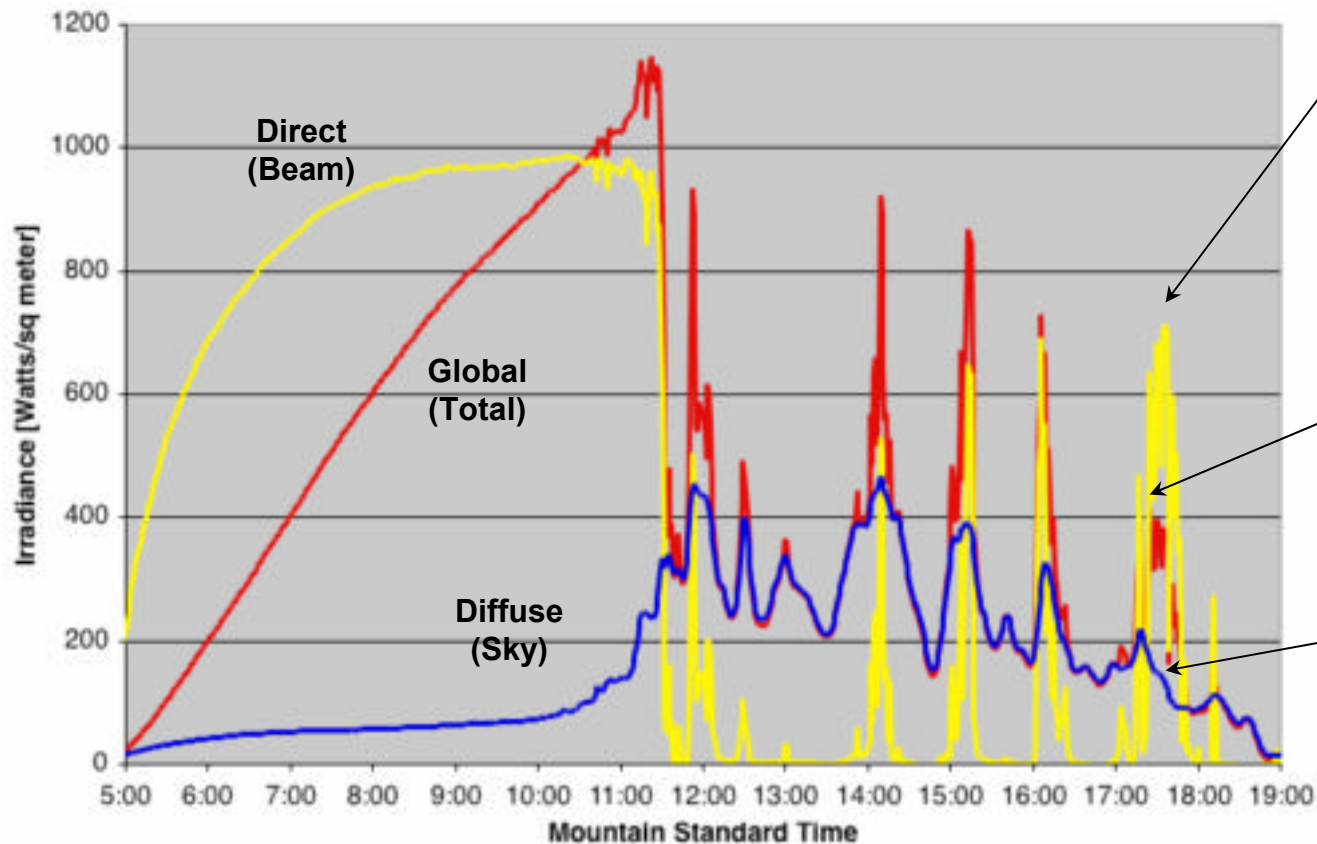


Figure 4. The LI-200SA Pyranometer spectral response is illustrated along with the energy distribution in the solar spectrum (8).

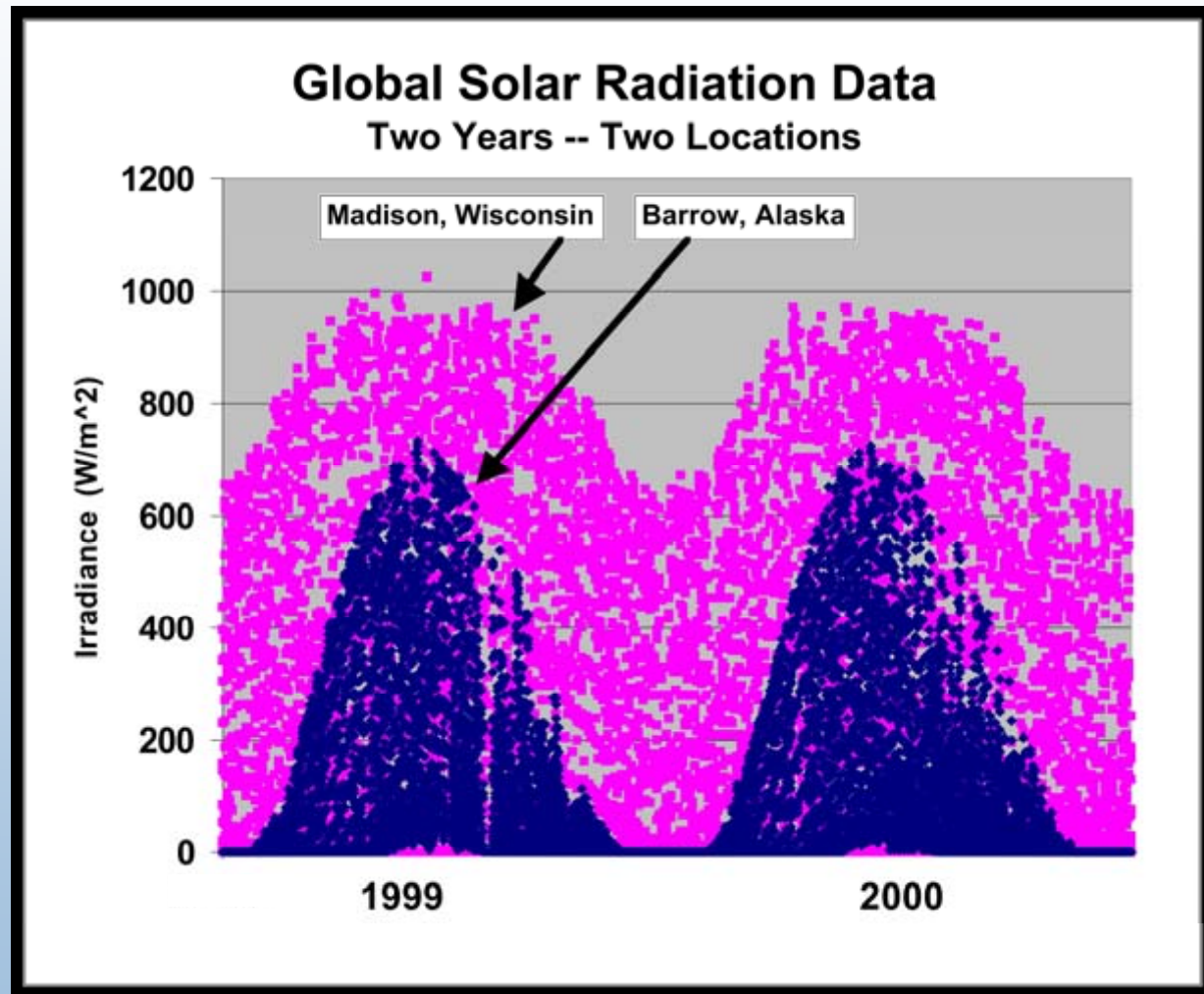
Partly Cloudy Sky

Solar Irradiance Measurements
Golden, Colorado 3 July 2004

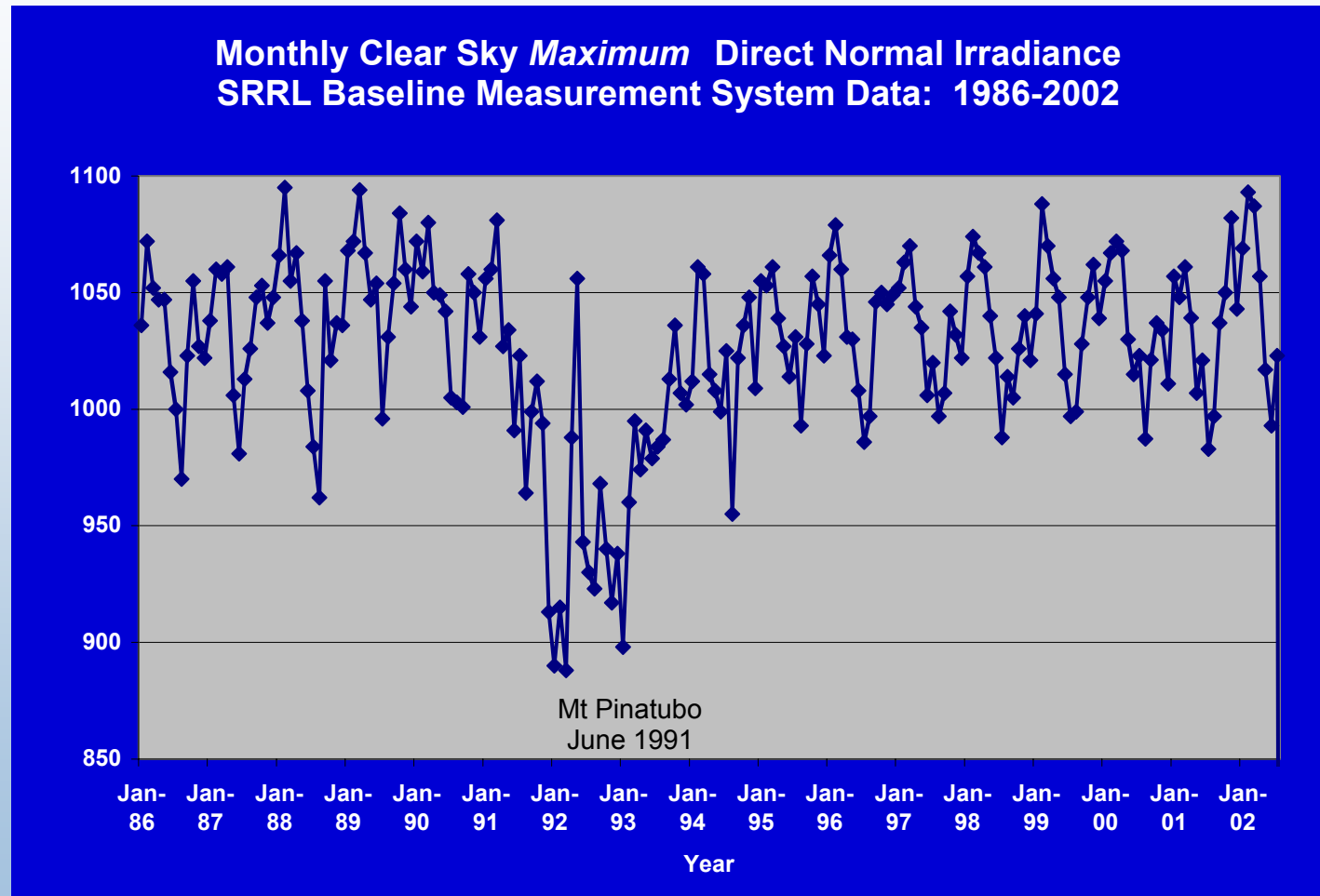


<http://www.nrel.gov/srri>

Changes with Time & Location: Annual Cycle

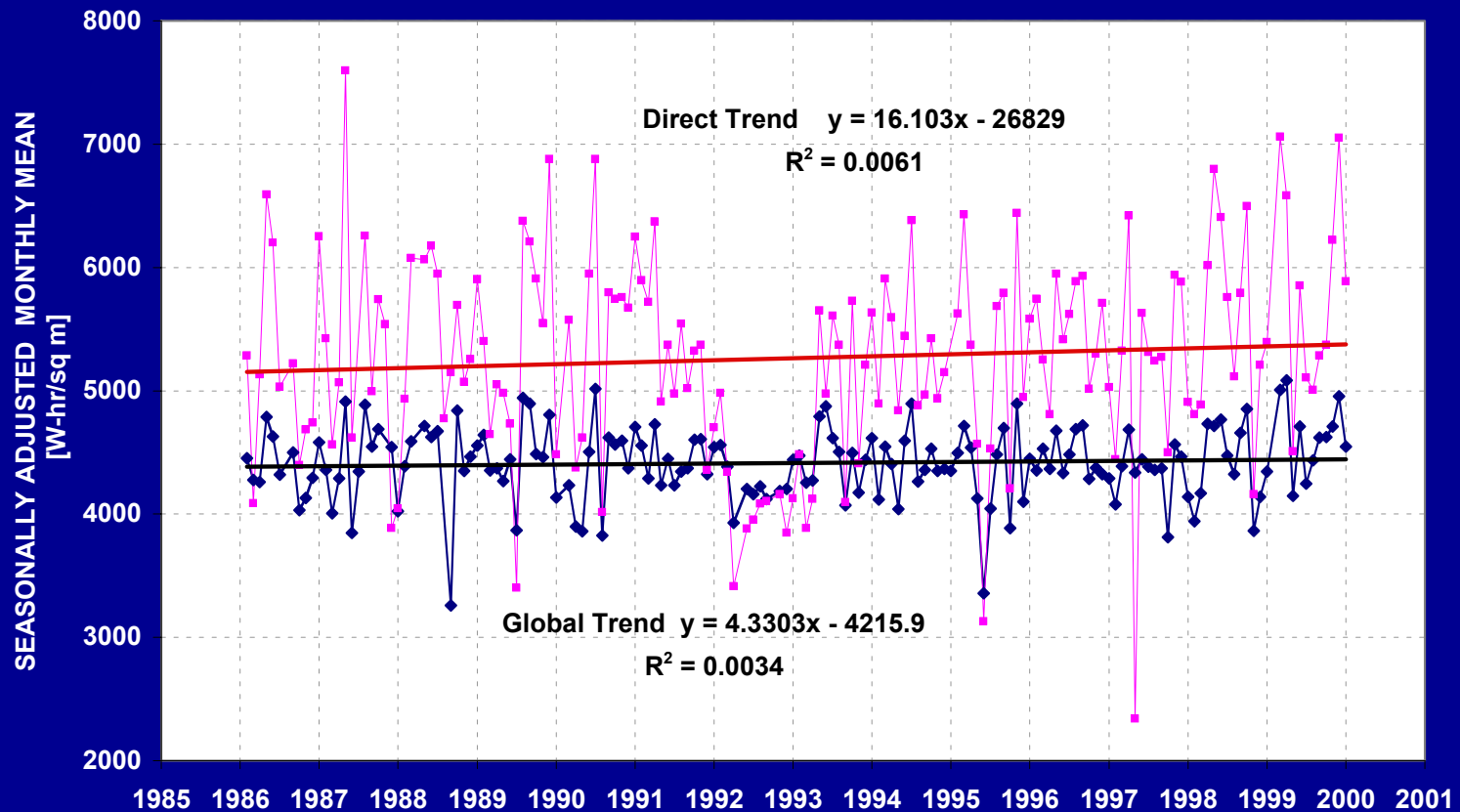


Changes with Time: Inter-annual



Changes with Time: Inter-annual

MONTHLY MEAN DAILY TOTALS Solar Radiation Research Laboratory 1986-2000



Spectral Distribution of Solar Radiation

Broadband Solar Radiation:

280 nm - 3,000 nm

(99% of “shortwave” irradiance at the surface)

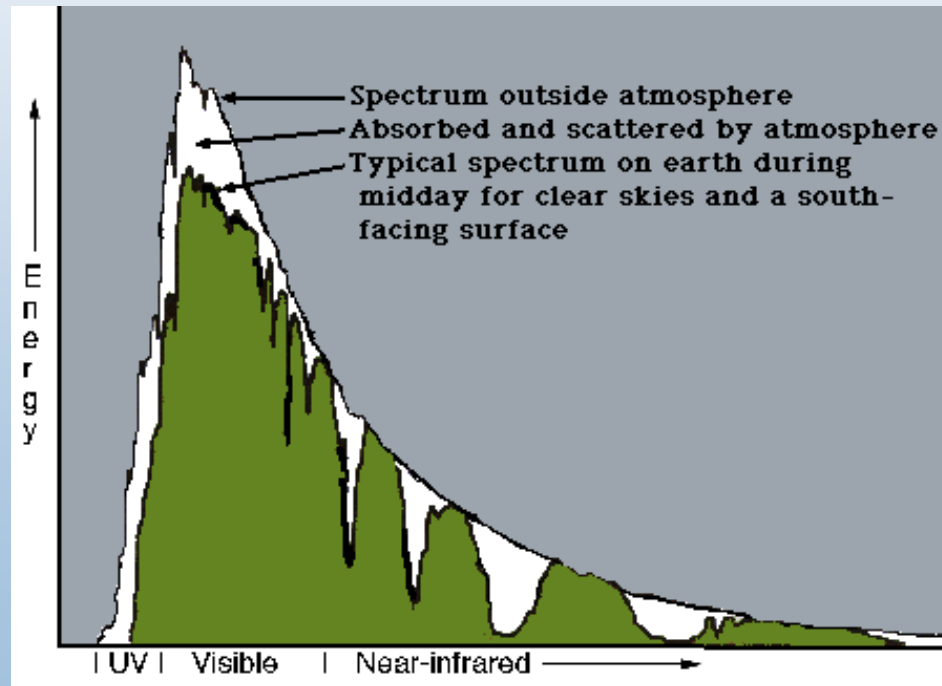


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Spectral Irradiance

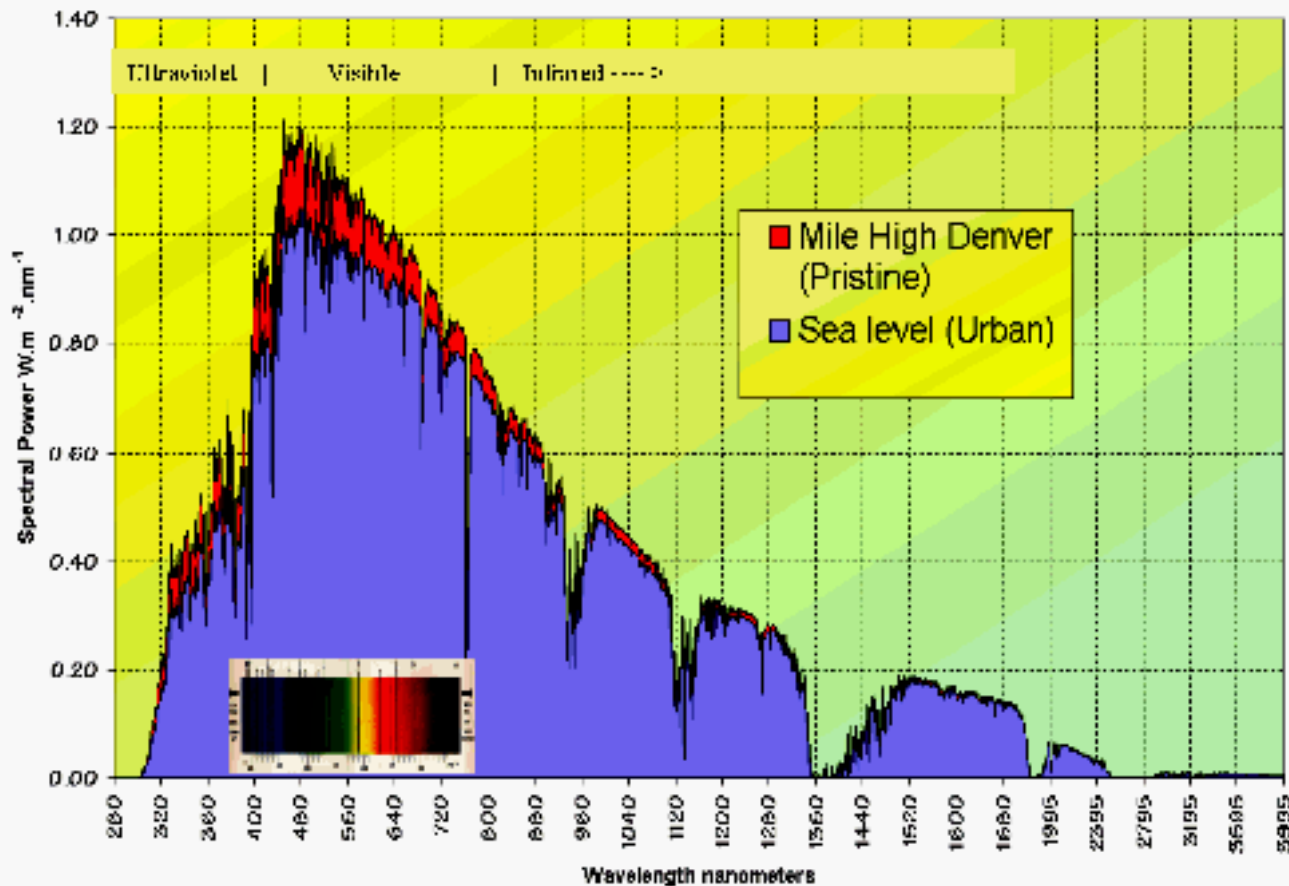
Basic Solar Spectral Regions:

- Ultraviolet.....200 - 400 nm
- Visible.....400 - 700 nm
- Infrared.....700 - 3000 nm

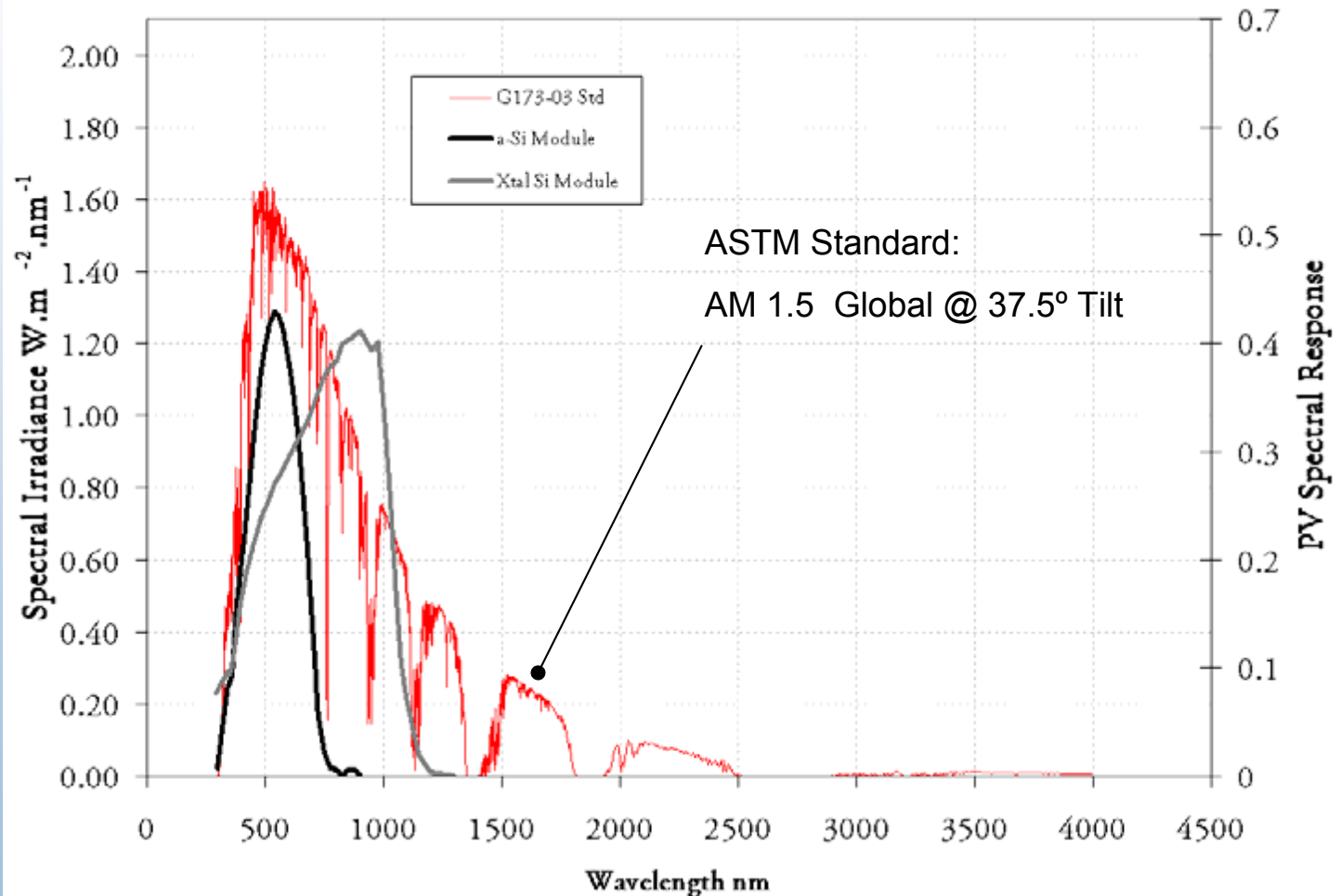


Follow the Photons!

Comparison of Sea Level and Denver Clear Sky Spectra
Modeled for typical 10 AM, 2 PM conditions in Summer

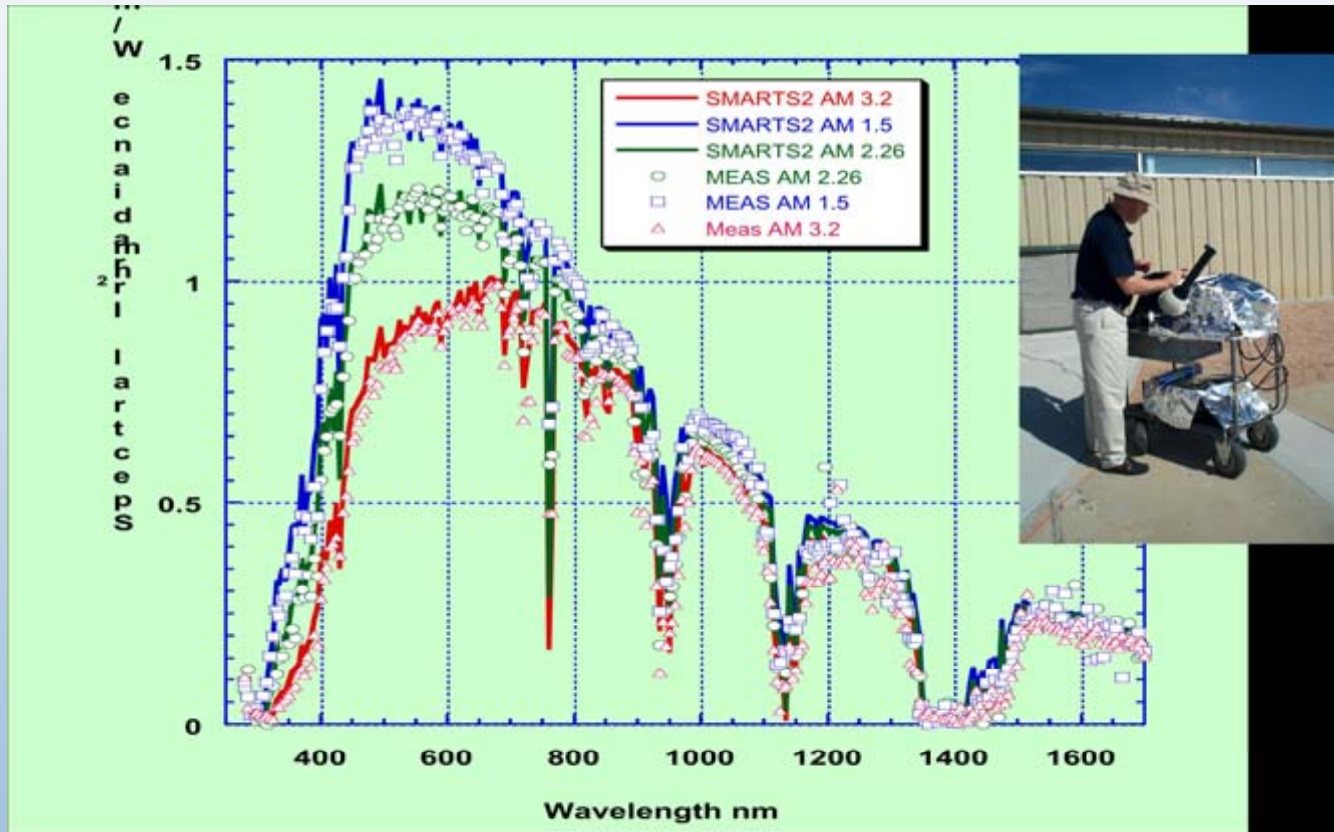


Photovoltaic Responses



Simple Model for Atmospheric Radiative Transfer of Sunshine

SMARTS



SMARTS

Extraterrestrial Spectrum (Card 7a)		Default Atmosphere Atmosphere (Card 3)		Gaseous Absorption and Pollution (Card 6)																																	
Aerosol Model (Card 8)	Turbidity (Card 9)	Albedo (Card 10)	Circumsolar (Card 13)	Scanning/Smoothing (Card 14)																																	
Extraterrestrial Spectrum (Card 7a)		Atmosphere (Card 3)		Gaseous Absorption and Pollution (Card 6)																																	
Aerosol (Card 8)	Atmos (Card 9)	Albedo (Card 10)	Circumsolar (Card 13)	Extra Scanning/Smoothing (Card 14)																																	
Illuminance Extra Illu (Card 15)		Output (Card 12)																																			
Solar Position (Card 17) <ul style="list-style-type: none"> <input type="radio"/> Input Zenith and Azi <input type="radio"/> Input Elevation and <input type="radio"/> Input relative Air Ma <input type="radio"/> Input Year, Month, D <input type="radio"/> Input Month, Latitud 		Output (Card 12) <ul style="list-style-type: none"> <input type="radio"/> Create .OUT file only, no spectral results <input type="radio"/> Create .OUT file only, with spectral results <input checked="" type="radio"/> Create .OUT and .EXT files, include spectral results in .EXT file only <input type="radio"/> Create .OUT and .EXT files, include spectral results in both files 																																			
Spectral range to be printed (nm) <table border="1"> <tr> <td>Minimum</td> <td>Maximum</td> <td>Interval (step)</td> </tr> <tr> <td>280</td> <td>4000</td> <td>.5</td> </tr> </table>		Minimum	Maximum	Interval (step)	280	4000	.5	Spectral Results <i>Note: Output order is as shown below and cannot be specified.</i>																													
Minimum	Maximum	Interval (step)																																			
280	4000	.5																																			
Record Number 1 of 1		<table border="0"> <tr> <td><input type="checkbox"/> Extraterrestrial irradiance</td> <td><input type="checkbox"/> Global horizontal photon flux</td> <td><input type="checkbox"/> Ozone optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Direct normal irradiance</td> <td><input type="checkbox"/> Diffuse horizontal photon flux</td> <td><input type="checkbox"/> Optical thickness from all trace gases</td> </tr> <tr> <td><input type="checkbox"/> Diffuse horizontal irradiance</td> <td><input type="checkbox"/> Direct normal photon flux</td> <td><input type="checkbox"/> Water vapor optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Global horizontal irradiance</td> <td><input type="checkbox"/> Rayleigh transmittance</td> <td><input type="checkbox"/> Uniformly mixed gas optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Direct horizontal irradiance</td> <td><input type="checkbox"/> Ozone transmittance</td> <td><input type="checkbox"/> Aerosol optical thickness</td> </tr> <tr> <td><input type="checkbox"/> Direct tilted irradiance</td> <td><input type="checkbox"/> Transmittance from all trace gases</td> <td><input type="checkbox"/> Aerosol single scattering albedo</td> </tr> <tr> <td><input type="checkbox"/> Diffuse tilted irradiance</td> <td><input type="checkbox"/> Water vapor transmittance</td> <td><input type="checkbox"/> Aerosol asymmetry factor</td> </tr> <tr> <td><input type="checkbox"/> Global tilted irradiance</td> <td><input type="checkbox"/> Uniformly mixed gas transmittance</td> <td><input type="checkbox"/> Zonal surface reflectance</td> </tr> <tr> <td><input type="checkbox"/> Experimental direct w/circumsolar</td> <td><input type="checkbox"/> Aerosol transmittance</td> <td><input type="checkbox"/> Local ground reflectance</td> </tr> <tr> <td><input type="checkbox"/> Experimental diffuse irradiance</td> <td><input type="checkbox"/> Beam radiation transmittance</td> <td><input type="checkbox"/> Atmospheric reflectance</td> </tr> <tr> <td><input type="checkbox"/> Circumsolar within radiometer</td> <td><input type="checkbox"/> Rayleigh optical thickness</td> <td></td> </tr> </table>			<input type="checkbox"/> Extraterrestrial irradiance	<input type="checkbox"/> Global horizontal photon flux	<input type="checkbox"/> Ozone optical thickness	<input type="checkbox"/> Direct normal irradiance	<input type="checkbox"/> Diffuse horizontal photon flux	<input type="checkbox"/> Optical thickness from all trace gases	<input type="checkbox"/> Diffuse horizontal irradiance	<input type="checkbox"/> Direct normal photon flux	<input type="checkbox"/> Water vapor optical thickness	<input type="checkbox"/> Global horizontal irradiance	<input type="checkbox"/> Rayleigh transmittance	<input type="checkbox"/> Uniformly mixed gas optical thickness	<input type="checkbox"/> Direct horizontal irradiance	<input type="checkbox"/> Ozone transmittance	<input type="checkbox"/> Aerosol optical thickness	<input type="checkbox"/> Direct tilted irradiance	<input type="checkbox"/> Transmittance from all trace gases	<input type="checkbox"/> Aerosol single scattering albedo	<input type="checkbox"/> Diffuse tilted irradiance	<input type="checkbox"/> Water vapor transmittance	<input type="checkbox"/> Aerosol asymmetry factor	<input type="checkbox"/> Global tilted irradiance	<input type="checkbox"/> Uniformly mixed gas transmittance	<input type="checkbox"/> Zonal surface reflectance	<input type="checkbox"/> Experimental direct w/circumsolar	<input type="checkbox"/> Aerosol transmittance	<input type="checkbox"/> Local ground reflectance	<input type="checkbox"/> Experimental diffuse irradiance	<input type="checkbox"/> Beam radiation transmittance	<input type="checkbox"/> Atmospheric reflectance	<input type="checkbox"/> Circumsolar within radiometer	<input type="checkbox"/> Rayleigh optical thickness	
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<input type="checkbox"/> Circumsolar within radiometer	<input type="checkbox"/> Rayleigh optical thickness																																				
Hour (local standard time, deci Latitude (deg, +N, Longitude (deg, +E, Time Zone (+E, 		Units: Irradiance in $W\ m^{-2}\ nm^{-1}$; Photon Flux in $10^{-3}\ cm^{-2}\ s^{-1}\ nm^{-1}$																																			
Select All Deselect All Enter Cancel																																					

Available from NREL: <http://rredc.nrel.gov>

Why Do We Need Solar Radiation Data?

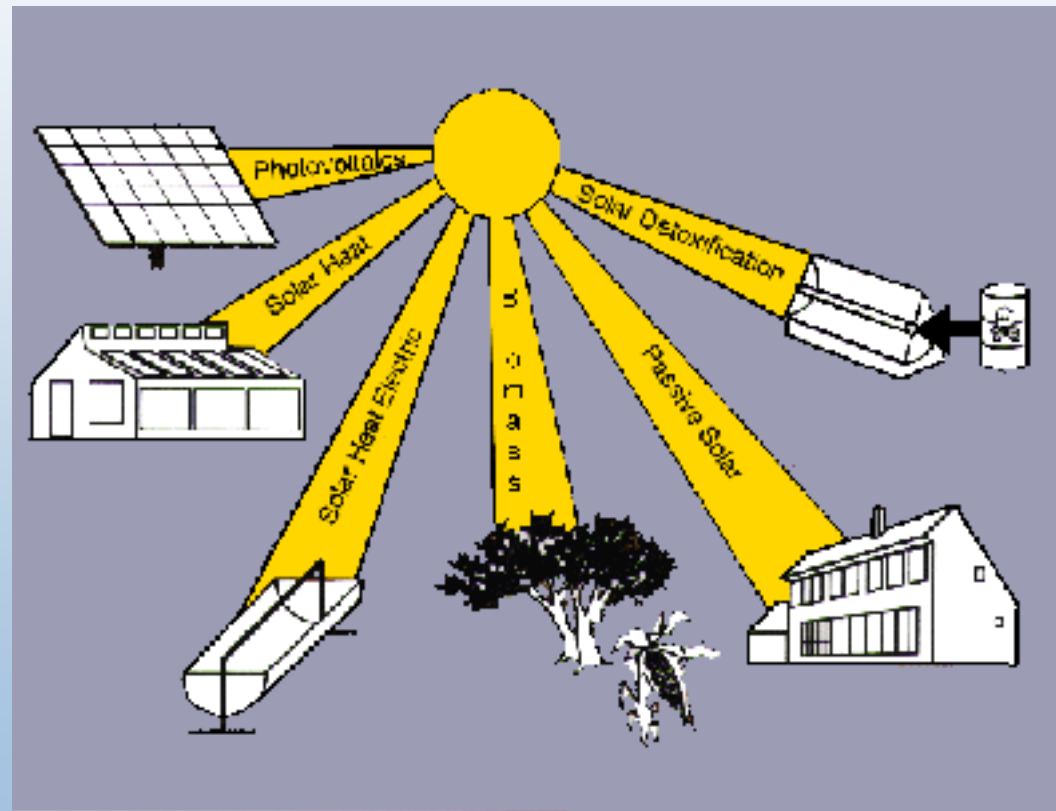
- | | |
|-----------------------|------------------------------|
| • Agriculture | Photosynthesis |
| • Astronomy | Solar Output Variation |
| • Atmospheric Science | Numerical Weather Prediction |
| • Climate Change | Energy Balance |
| • Health | UV effects on skin |
| • Hydrology | Evaporation |
| • Materials | Degradation |
| • Oceanography | Energy Balance |
| • Photobiology | Light and Life |
| • Renewable Energy | Sustainability |

Why Do We Need Solar Radiation Data?

Renewable Energy

The amount of solar energy reaching the earth's land areas in 1 hour is enough to supply the U.S. energy needs for 1 year (~100 Quads/yr)

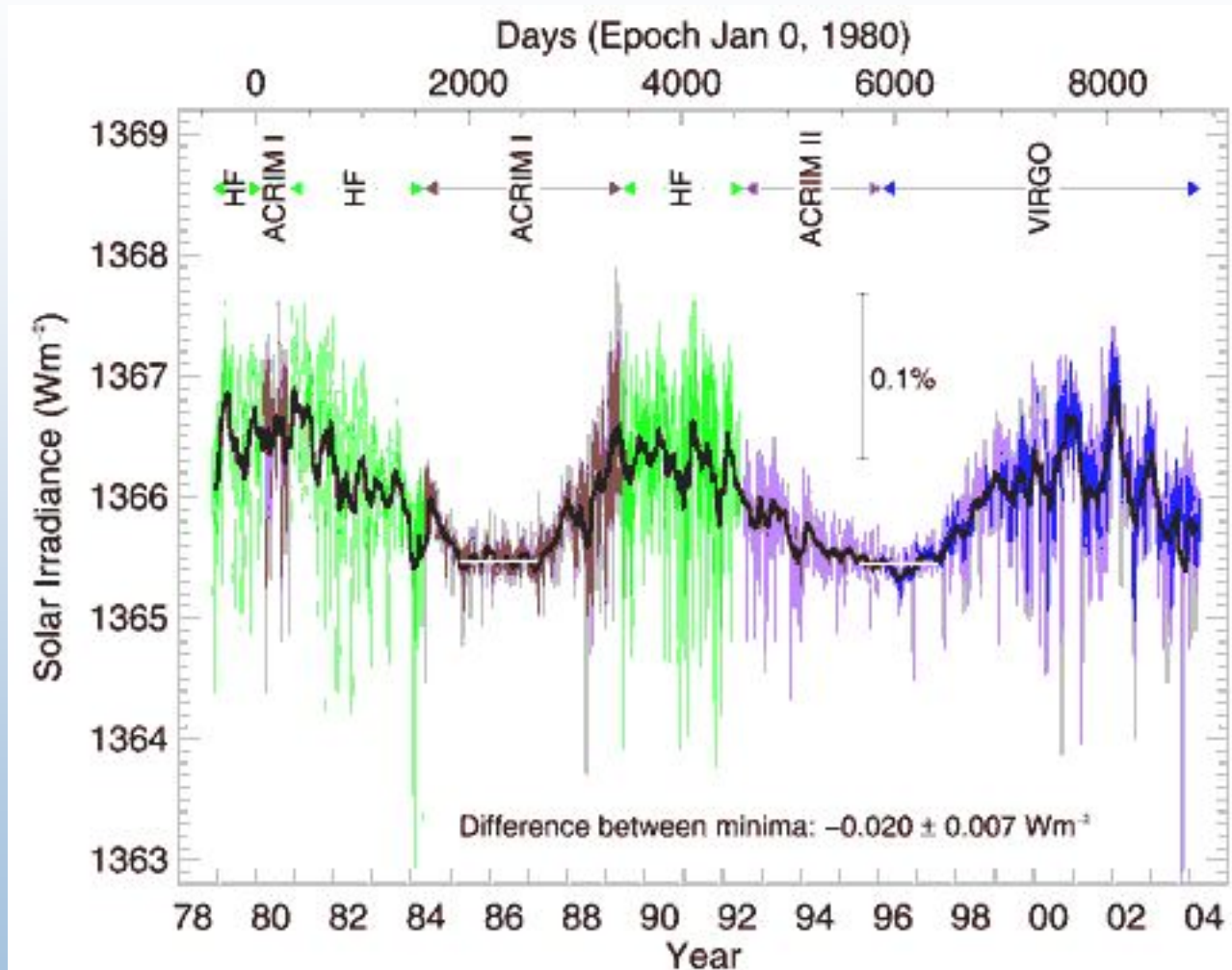
- Photovoltaics
- Solar Heat-thermal
- Solar Heat-electric
- Solar Fuel-biomass
- Passive Solar Lighting
- Building HVAC
- Solar Detoxification



What Influences the Amount of Solar Radiation?

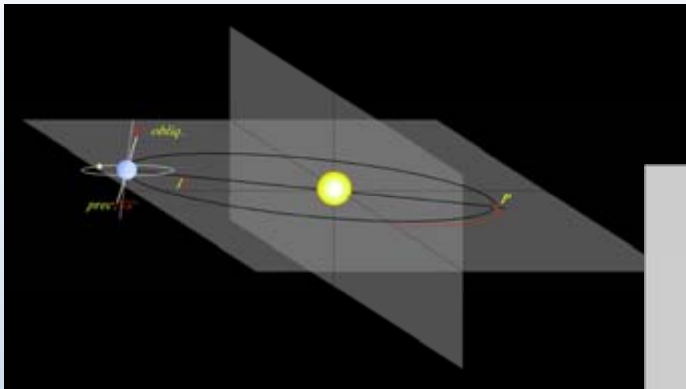
- Solar output
 - Earth-Sun distance
 - Clouds
 - Water vapor
 - Air pollution
 - Smoke from forest fires
 - Volcanic ash
 - Location
 - Time of day
 - Season
- 11 year solar cycle
3.5% annual variation
Dominant factor
Selective absorber
40% less direct
Natural or man-made
Global effect for years
- Solar position
- 

Solar “Constant”



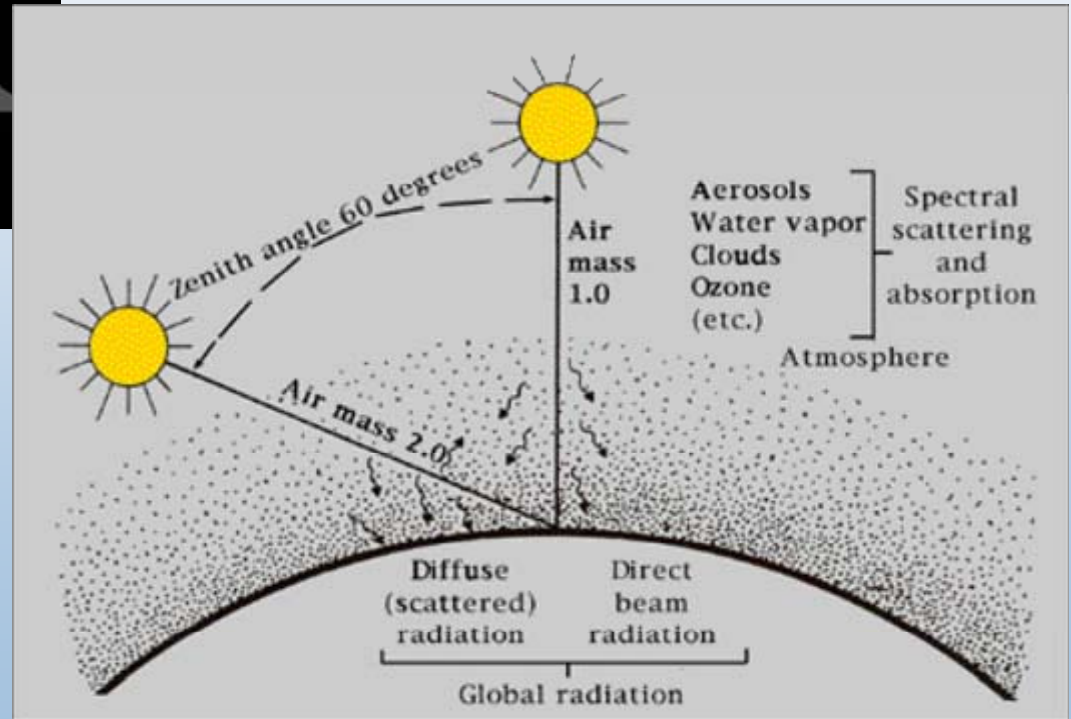
World Radiation Center, Davos, Switzerland
<http://www.pmodwrc.ch/>

What Influences the Amount of Solar Radiation?



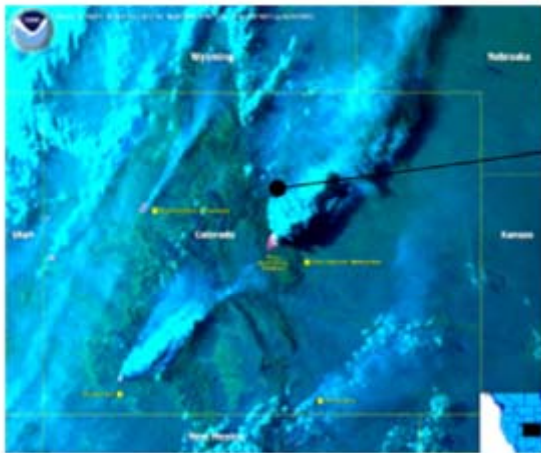
Earth's Orbit:

- Earth-Sun distance
- Relative tilt
- Time of day



What Influences the Amount of Solar Radiation?

SRRL Measures Effects of Forest Fires on Solar Radiation



← NOAA Satellite Image

NREL

SRRL "SKYCAM" Image →
June 10, 2002



Fuzzy Sun and Shadows:
Increased scattering yields Higher-than-normal
Circumsolar Radiation

Changes in Direct "Beam" Irradiance

-A- Morning Haze Before Shift in Wind:

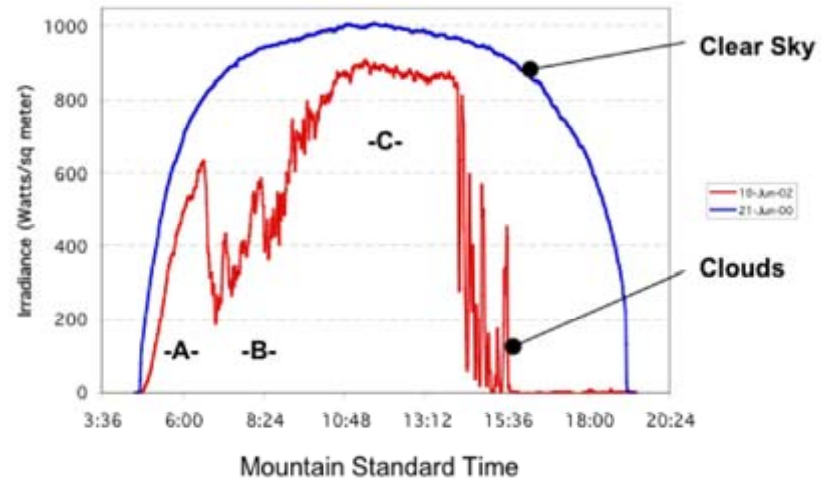
75% of Clear Sky (7:00)

-B- Thick Smoke Cloud:

23% of Clear Sky (7:30)

-C- Midday Haze:

90% of Clear Sky



How Do We Use Solar Radiation Data?

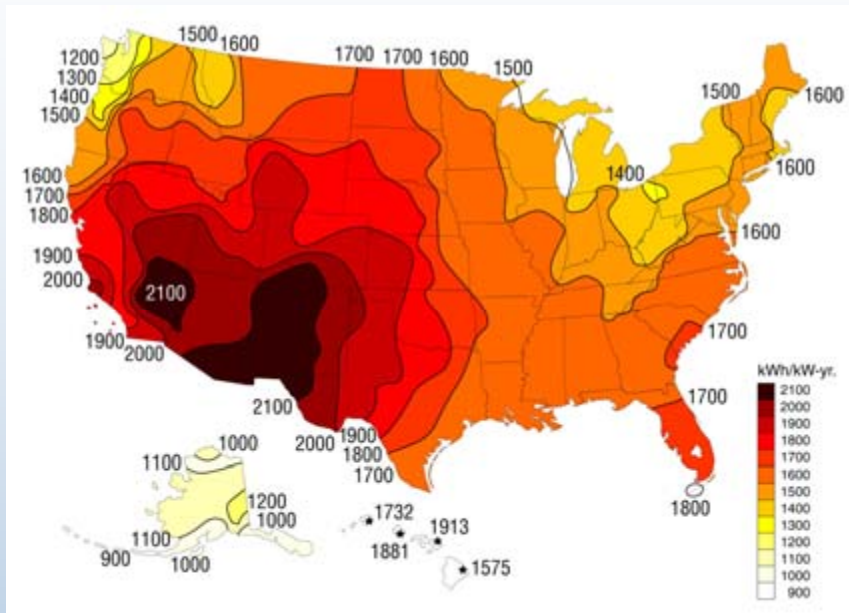
- Technology Selection
- Siting
- System Design
- Performance Monitoring



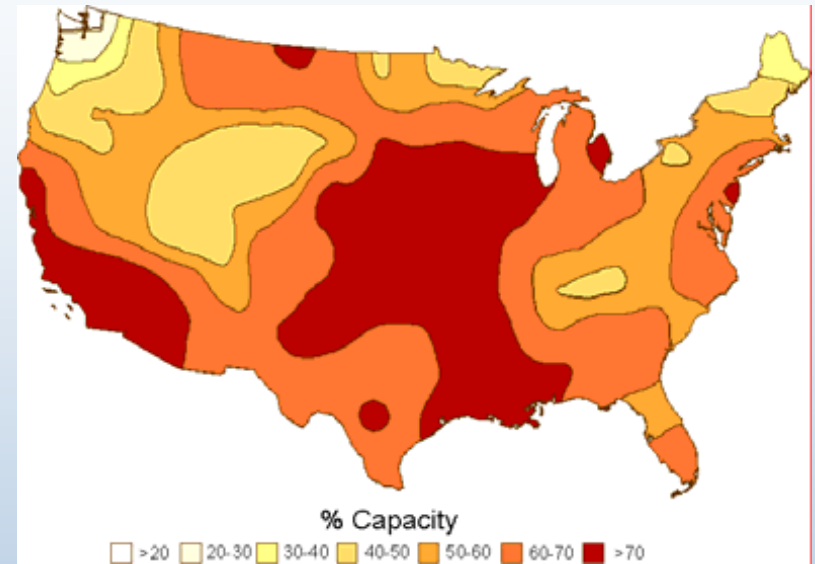
Flat Plate and
Concentrating Collectors



PV Energy kWh/kW-yr



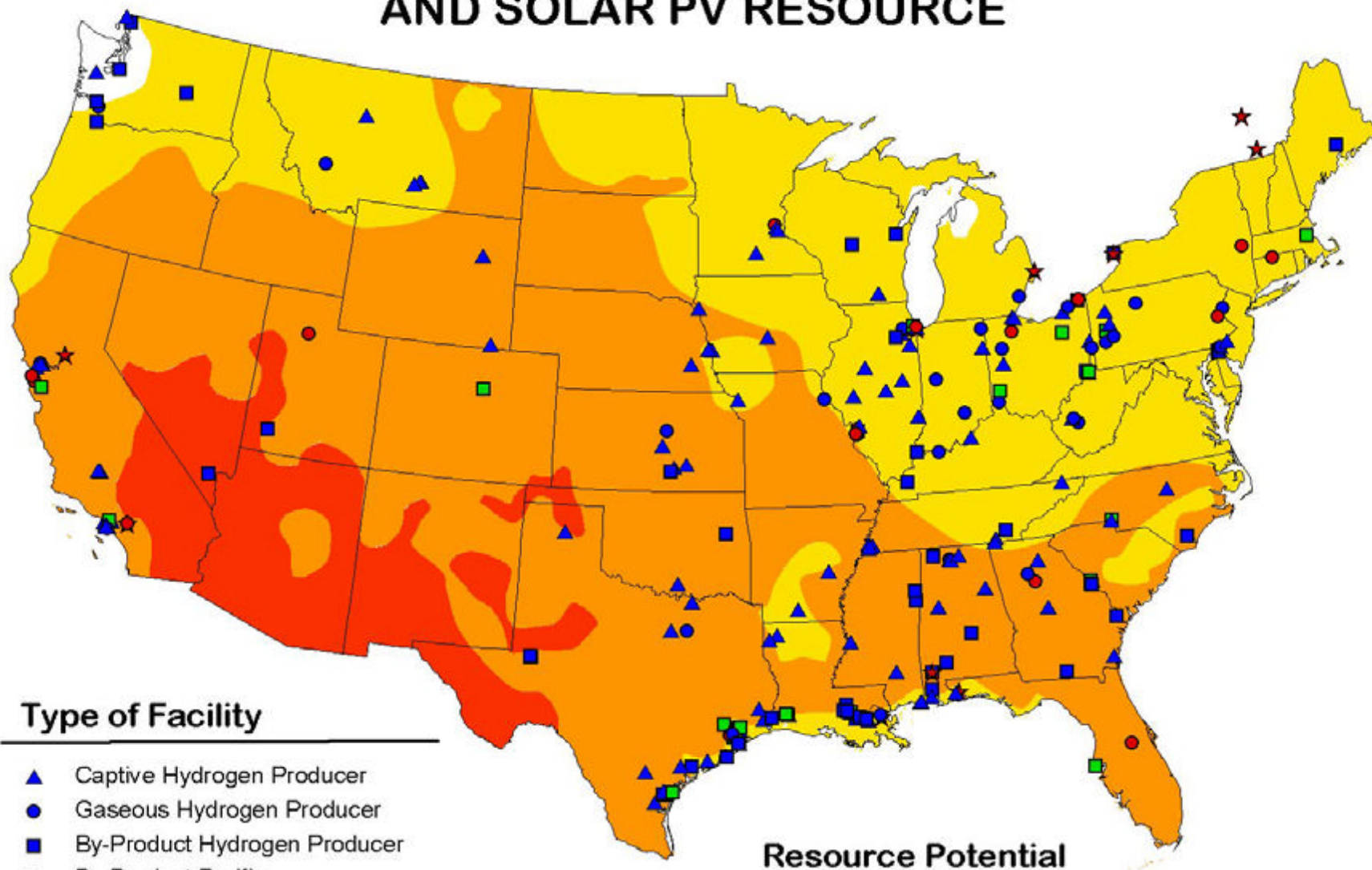
Effective Load Carrying Capacity



Source: Christy Herig (NREL) and Richard Perez (SUNY/Albany)

- PV can provide peak shaving in many parts of U.S.
- During off-peak periods, PV capacity can be applied to hydrogen generation

HYDROGEN FACILITIES AND SOLAR PV RESOURCE



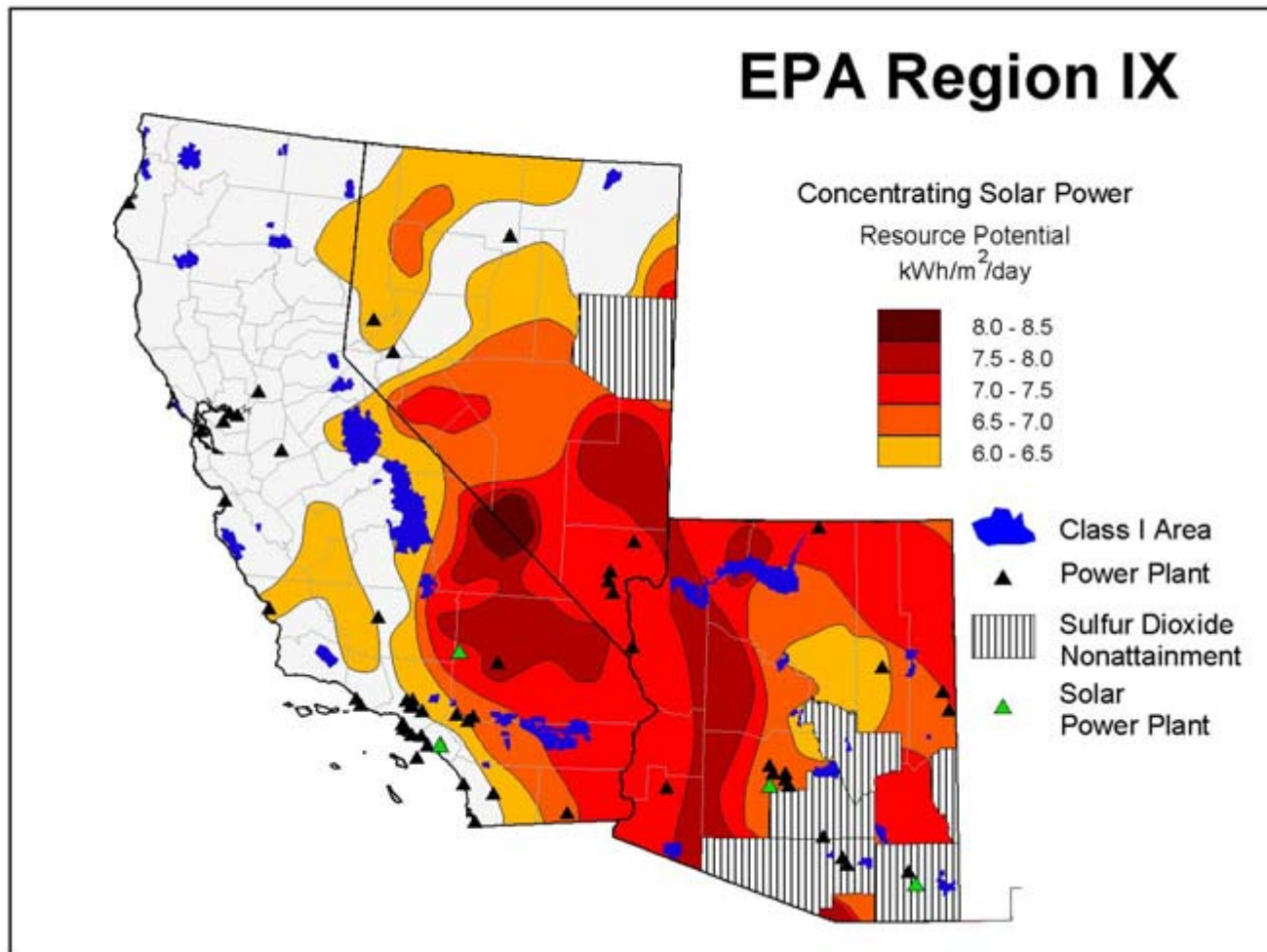
Type of Facility

- ▲ Captive Hydrogen Producer
- Gaseous Hydrogen Producer
- By-Product Hydrogen Producer
- By-Product Purifier
- ★ Liquid Hydrogen Producer
- Satellite Terminal
- Undetermined

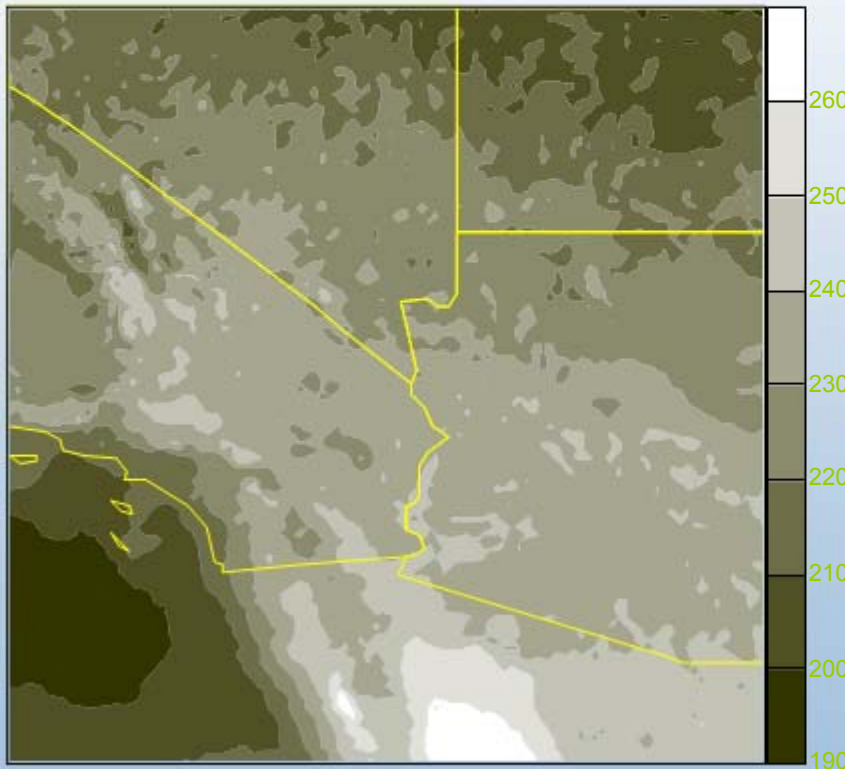
Resource Potential

- Excellent
- Good
- Moderate

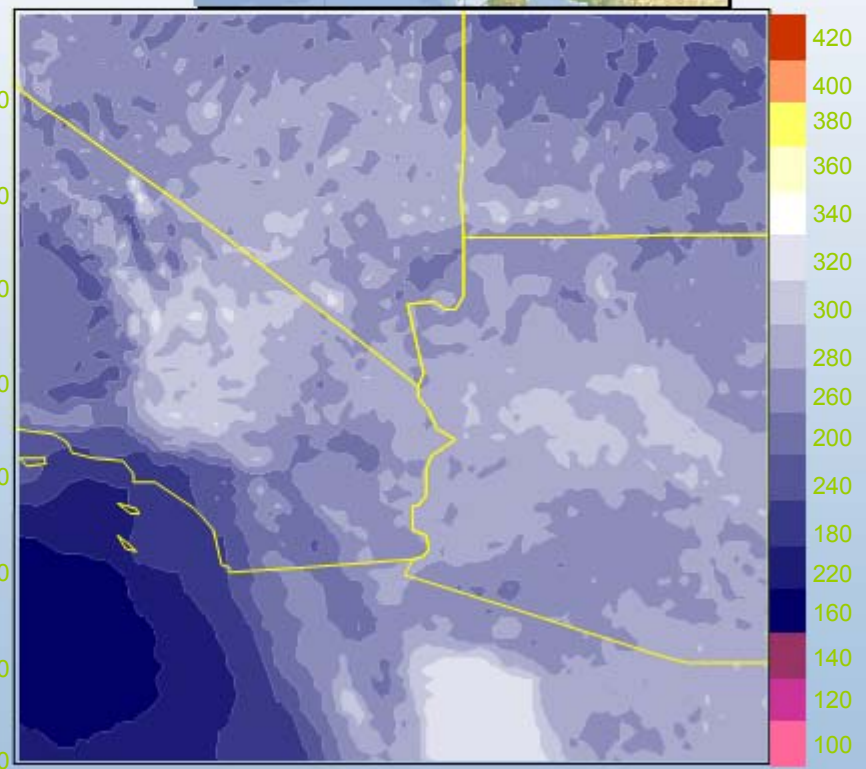
An Integrated Analysis Utilizing GIS can Assist With Energy and Environment Planning Efforts



Satellite-Derived Techniques Provide Improved Site-Time Coverage (SUNY/Albany)



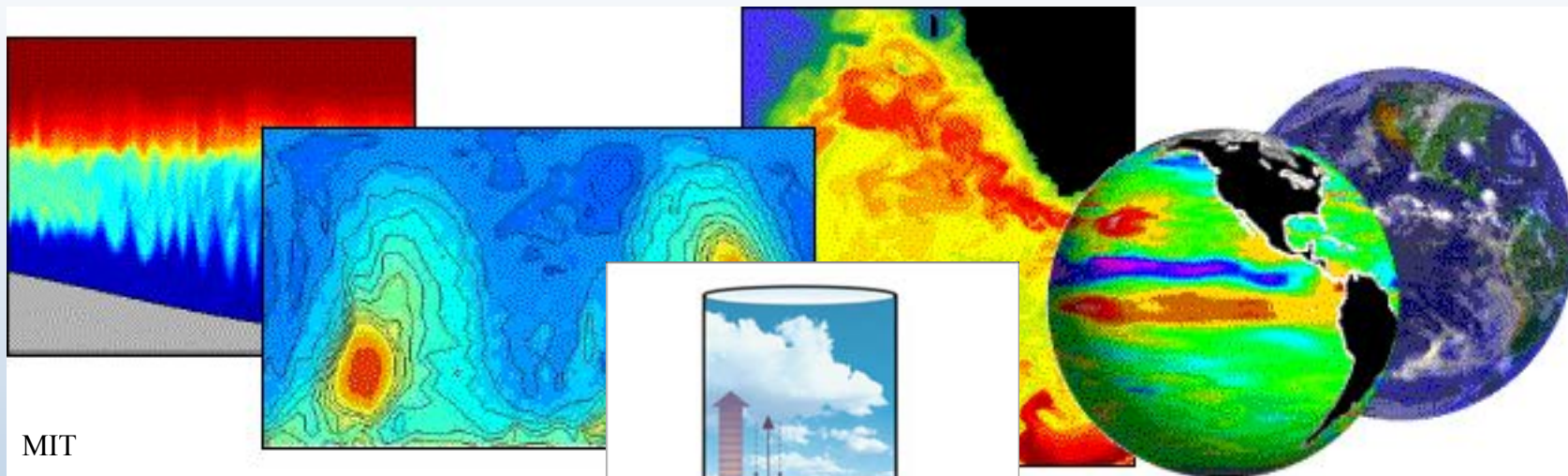
GLOBAL IRRADIANCE (average W/sq.m)



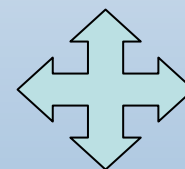
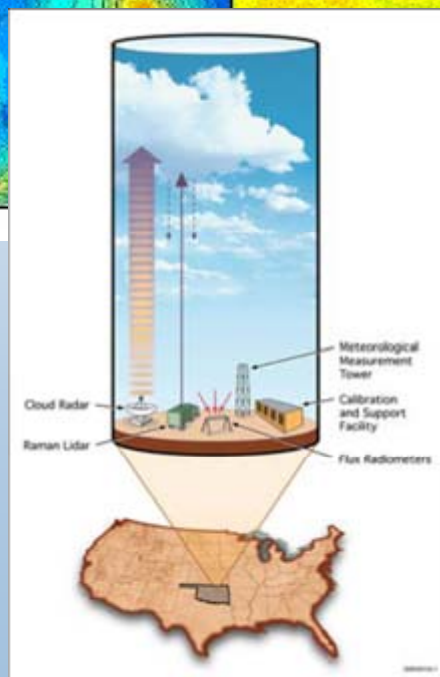
DIRECT IRRADIANCE (average W/sq.m)

How Do We Use Solar Radiation Data?

General Circulation Model Development



MIT



Radiant Fluxes?

DOE/Atmospheric Radiation Measurement (ARM) Program

How Accurate Do the Data Need to Be?

- What are the risks?
 - Cost/Benefit of Resource Assessment approach
- What is the application?
 - Daylighting & building thermal performance
 - Concentrating Collector Solar Power Plant
 - Cloud forcing analyses for climate change research
- What is the period of interest?
 - Measurement uncertainties decrease with longer averaging intervals (averaging can remove random errors)
 - Recent data more accurate than historical records (technology advancements)

How Accurate Do the Data Need to Be?

What is possible?

Measurement Uncertainty Estimates*

	Pyrheliometer (Direct Normal)	Pyranometer (Global)
Calibration	$\pm 1.6\%$	$\pm 4.2\%$
Field Data (Best practice)	$\sim \pm 5\%$	$\sim \pm 5\%$

*
Instantaneous data intervals

How Will We Meet Our Solar Radiation Data Needs?

Research Activities:

- Solar Radiation Research Laboratory
 - Metrology
 - Optics
 - Electronics
 - Data Acquisition
- Photovoltaic Program
 - Radiometric Measurements
- Climate Change
 - Broadband Radiometer Mentor
- Collaborations
 - WMO, UNEP, NCAR, NOAA, state & local govt, academia

Solar Radiation Research Lab



- Baseline Measurements
- Radiometer Calibrations
- Instrument Development
- Station Operator Training



Solar Radiation Research Lab



Baseline Measurements
(98 data elements)

<http://www.nrel.gov/midc>



Rotating Shadowband Pyranometer

Radiometer Calibrations



World Radiometric Reference

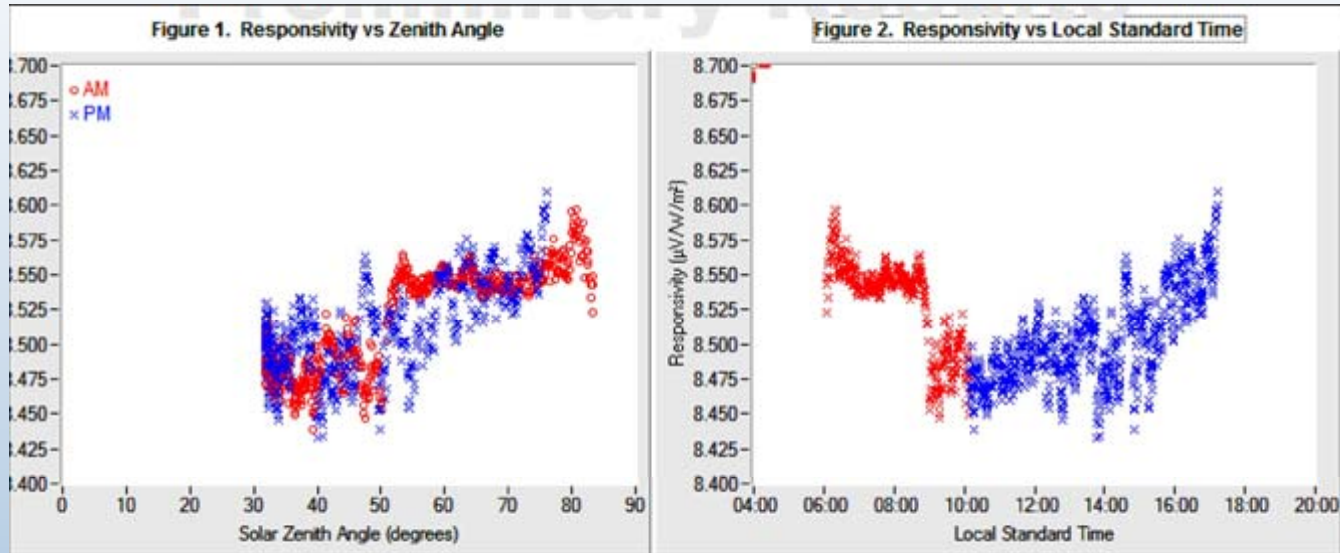


NREL Transfer Standards

NPC
At SRRL



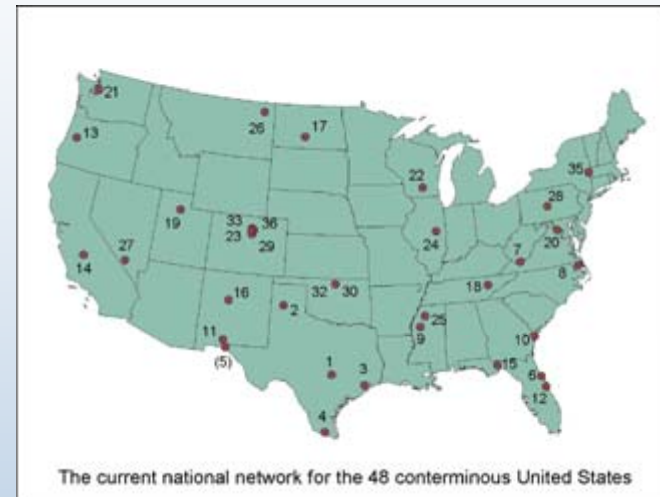
Radiometer Calibrations



National Solar Radiation Data Base



NSRDB Stations
(1961-1990)



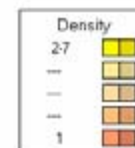
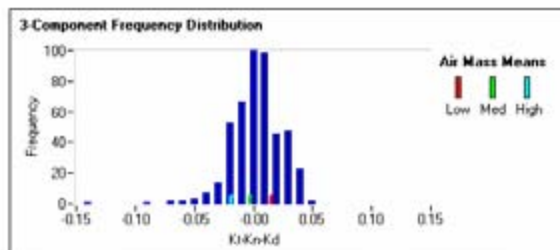
Solar Measurement Stations
(1990 - Present)

Automatic Data Quality

SRRLH, SRRL Hourly - June

Global / Direct

3 Component Filtering: Off
K-Space Threshold: —
Integration Time (min): 60
Density Plotting: Equal Freq



Curves
KrMax: 80
KdMax: 80
Left: 4.9
Right: 1.12

In	284
Out	20 (6.6 %)
Active	304
Ignored	0
Total	304
Err (L)	1.6 %
Err (R)	4.3 %

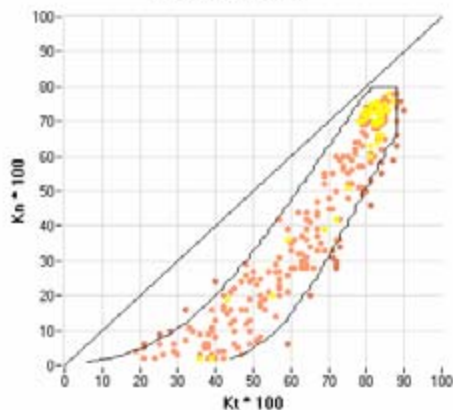
Curves
KrMax: 75
KdMax: 85
Left: 4.9
Right: 1.11

In	177
Out	10 (5.3 %)
Active	187
Ignored	1
Total	188
Err (L)	1.6 %
Err (R)	3.7 %

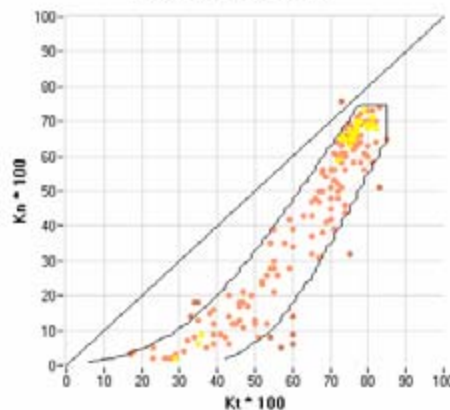
Curves
KrMax: 65
KdMax: 70
Left: 4.8
Right: 1.9

In	92
Out	9 (8.9 %)
Active	101
Ignored	0
Total	101
Err (L)	3.0 %
Err (R)	5.0 %

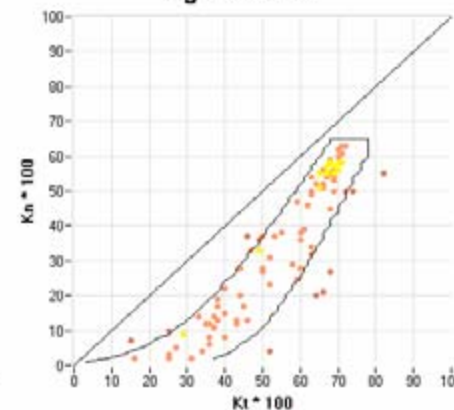
Low Air Mass



Medium Air Mass



High Air Mass



Where Can You Obtain solar Radiation Data?

- Renewable Resource Data Center
 - <http://rredc.nrel.gov>
- Measurement & Instrumentation Data Center
 - <http://www.nrel.gov/midc>
- NREL Map Server
 - <http://www.nrel.gov/maps>
- World Radiation Data Center
 - <http://wrdc-mgo.nrel.gov>
- National Climatic Data Center
 - <http://www.ncdc.noaa.gov>
- DOE Atmospheric Radiation Measurement Program
 - <http://www.arm.gov>
- NOAA Climate Monitoring & Diagnostic Laboratory
 - <http://www.cmdl.noaa.gov/star>
- NOAA Surface Radiation Research Branch
 - <http://www.srrb.noaa.gov>

Key Points

- Accurate information is important for policy decisions, technology selection, siting, designing, and monitoring the performance of solar energy conversion systems
- Accurate measurements are important for model development
- The work we do to improve solar measurements
 - Calibration
 - Instrument characterization
 - Measurement techniques (operations and maintenance, radiometer selection, installation considerations, etc.)
 - Data Quality Assessment
 - Training
- Data distribution to meet user needs (MIDC, RReDC, NSRDB)

Solar Radiation Measurement

Thank you!

Questions?

POP Quiz

Write the relationship between Global, Direct, & Diffuse irradiance.

$$\text{Global} = \text{Direct Normal} * \cos(Z) + \text{Diffuse}$$

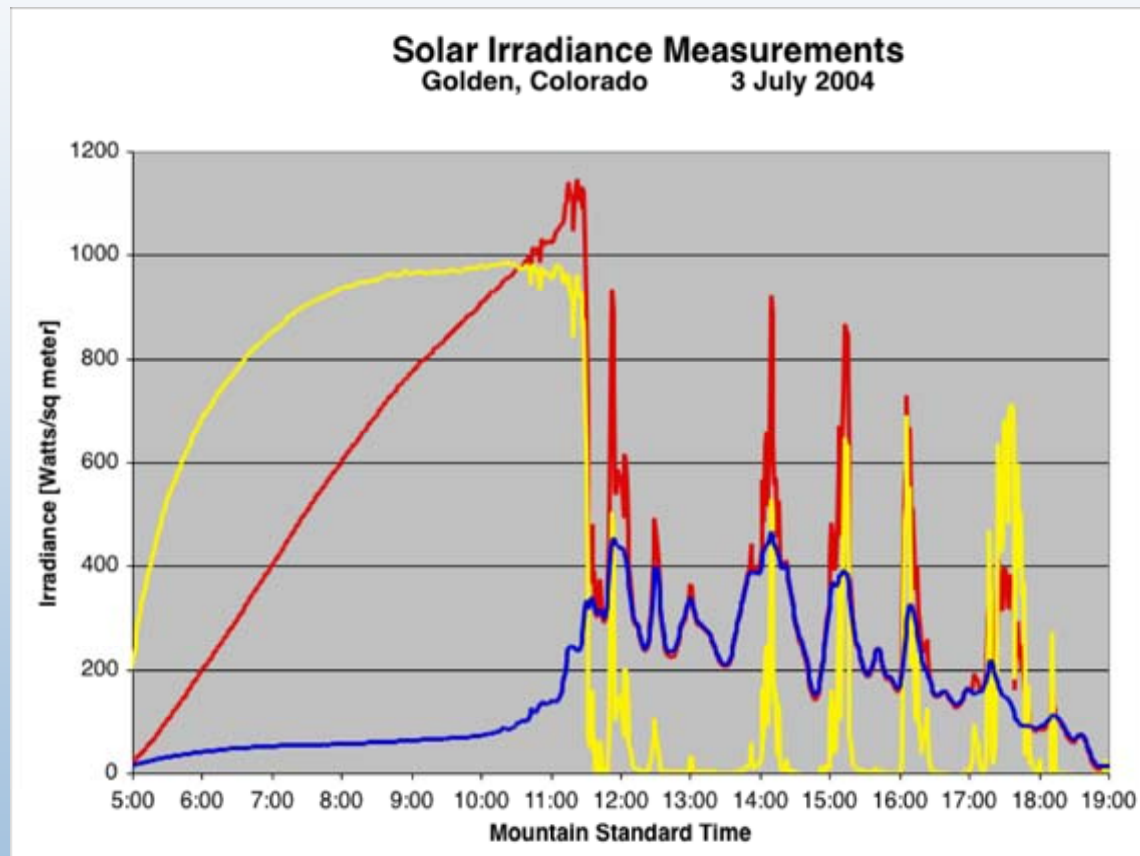
POP Quiz

Indicate which properties (quick, accurate, or cheap) apply to these pyranometer detector types:

- ✓ Photodiode Fast, Cheap, Spectrally selective
- ✓ Thermopile Accurate, \$\$, Slow

POP Quiz

T/F: The Global irradiance can never exceed the solar constant.



POP Quiz

The presently accepted value of the Solar Constant:

- a) 1.96 Langleys per minute
- b) 1366 Watts per square meter
- c) 432.7 BTUs per hour-square foot
- d) All of the above

